Anomalous Loss and Propagation in Photonic-crystal Waveguides

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To begin with, we present a new semi-analytical method that can predict losses due to disorder in photonic-crystal waveguides (whereas brute-force methods are nearly prohibitive), use it to predict a measurable *decrease* in surface-roughness loss due to a bandgap in a realizable structure, and show what designs enable this effect [1]. Our method is based on the decades-old "volume-current method" (or 1st Born approximation to the Green's function), where a perturbation $\Delta\varepsilon$ is modeled as a current $\mathbf{J} \sim \Delta\varepsilon\mathbf{E}$ in terms of the unperturbed field $\mathbf{E}$; we show, however, that a straightforward application of this idea for high-contrast nanophotonics can lead to an order-of-magnitude error in the predicted loss. Instead, the correct method for a surface "bump" with volume ΔV on an interface between ε_1 and ε_2 uses a current $\mathbf{J} \sim \left[\frac{\varepsilon_1 + \varepsilon_2}{2} \alpha_\parallel \mathbf{E}_\parallel + \varepsilon\gamma_\perp \mathbf{D}_\perp \right] \Delta V$, where $\alpha_\parallel$ and $\gamma_\perp$ are polarizabilities that must be computed numerically (via a small calculation). Thus, we are able to quantitatively model an "apples-to-apples" comparison of a 3d strip waveguide with the same strip surrounded by a photonic-crystal slab, and further explore our theorem [2] that a photonic band gap, all other things equal, reduces radiation and does not change reflection loss from weak disorder.

A related prediction (which we presented in PECS V) is that reflection losses scale inversely with the square of group velocity, making slow-light devices a challenge. To minimize disorder, we consider a fiber-based design, and predict unusual slowing, reversing, and trapping of light by adiabatic tuning of a *negative* group-velocity fiber [3]. Finally, we turn to another fiber design which has recently been fabricated at MIT along with a nearby start-up, OmniGuide Communications Inc., which circumvents the problem of loss by exploiting a hollow core design to achieve record transmissions at 10.6µm wavelengths, and we show how this has recently enabled a life-saving new endoscopic surgical procedure.

[1]   S. G. Johnson *et al.*, "Roughness losses and volume-current methods in photonic-crystal waveguides," *Applied Physics B*, in press (special issue, summer 2005).
[2]   M. L. Povinelli *et al.*, *Appl. Phys. Lett.* **84**, 3639 (2004).
[3]   M. Ibanescu *et al.*, *Phys. Rev. Lett.* **92** (6), 063903 (2004).
[4]   C. Anastassiou *et al.*, *Photonics Spectra* (March 2004).

Slow light - opportunity for photonic crystals ?

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There has been much excitement in recent years over the ability to slow down light, with opportunities for the realisation of optical delay lines and memories. The pioneers exploited the phenomenon of electromagnetically induced transparency in atomic systems, e.g. bringing light almost to a standstill in ultracold atoms. More recently, EIT slow light has also been reported in solid state systems. In contrast, slowdown factors in photonic crystals are much lower (typical values of c/100 to c/1000 [1] are being reported), yet photonic crystals offer a key advantage: Bandwidth. Using the bandwidth x slowdown factor as a figure of merit, photonic crystals offer clear advantages over EIT systems. Furthermore, using their well-known scaling capability, they can be tuned to any wavelength of interest and due to their dielectric nature, their response is entirely linear. Different photonic crystal-based concepts for slow light generation and their practical realisation will be discussed.

[1] H.Gersen, T.J. Karle et al., "Real-space observation of ultraslow light in photonic crystal waveguides", PRL 94, 073903, 2005.

Harnessing the Slow Light
in Photonic Crystal Waveguides

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Photonic crystals (PhC) are often touted as a powerful system for being able to mold light on the wavelength scale and hence are a strong contender for enabling on-chip optical integration. Perhaps the most interesting property of PhC, however, is their unique dispersive behavior that has implications for broad range of possible applications as dispersion compensators, optical buffers and optical memory. The ability to structurally engineer the dispersion in photonic crystals (PhC) and relatively wide bandwidth response make photonic crystals a promising system to explore this strongly dispersive regime when the group velocity of light is significantly reduced.

We will review progress in exploration of slow light phenomena in membrane-type SOI photonic crystal waveguides. Coupling issues, both off-chip and coupling to the slow group velocity mode in the PhC waveguide, will be discussed. We experimentally demonstrate an over 300-fold reduction of the group velocity in silicon photonic crystal waveguide using integrated Mach-Zehnder interferometer. We show fast (100ns) and efficient (2mW electric power) active control of the group velocity dispersion by localized heating of the photonic crystal waveguide with an integrated micro-heater.

High efficiency LEDs by Photonic Crystal-assisted extraction

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We are progressively approaching the physical limits of microcavity LEDs (MC-LEDs) for high brightness, high efficiency LEDs. They are promising high efficiency devices and they offer the very attractive prospect of full planar fabrication process. However, to compete with other high efficiency LED schemes, they need to approach or surpass the 50 % efficiency mark. We first explore the limits of planar MC-LEDs in both the GaAlInAsP and GaInAlN materials systems, and show that the single-step extraction limit is 40 % at best, with most of non-extracted light emitted into guided modes.

We then discuss the various Photonic Crystal (PhC) structures that have been proposed to control spontaneous emission, and possibly enhance it, starting with the pioneering paper of Eli Yablonovitch. Funneling emission in one or a few channels has not yet been demonstrated. Even suppressing or enhancing the overall rate in photoluminescence experiments still appears difficult, for a variety of reasons.

We will concentrate on extracting waveguided light. One uses PhCs as mirrors or diffracting elements, for a variety of purposes : in-plane microcavities, out-of plane scatterers, etc. We will show recent results on GaN based PhC LEDs. A detailed analysis of angular resolved emission patterns allows to determine the PhC dispersion curves, and the extraction efficiency for the various waveguided modes.

Optimal design of a PhC extractor is strongly dependent on the material. In GaAs for instance, simple PhCs appear to lack the omnidirectional extraction properties required. However, more rotation-invariant PCs like Archimedean tilings allow to obtain such extraction with added efficiencies already in the 10% range.
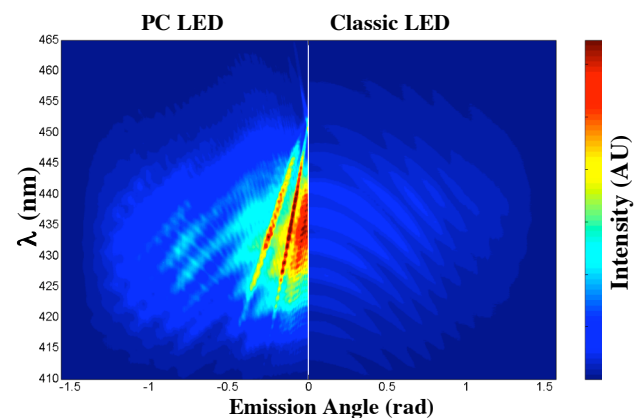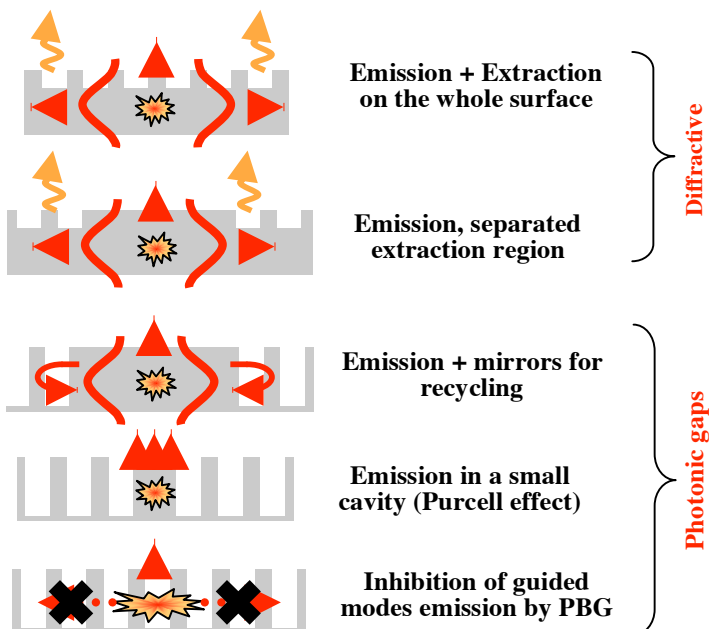
Left : various schemes for PhC-assisted light sources
Top : Angular resolved spectra of a PhC LED versus a classic LED in GaN

Tuning conditions between quantum dots and photonic crystals

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The possibility of developing a single photon source with a controlled emission directionality and enhanced emission rate by using quantum dots (QDs) coupled to a high Q photonic crystal (PC) opens important technological applications e.g. single photon emitters and detectors. Hence, understanding and controling this coupling is essential if the weak or strong coupling regime is to be routinely achieved. Coupling conditions are however, very demanding, since both the position of the QD and its frequency must be tuned to the PC mode location and the ultra sharp resonant frequency.

We will demonstrate using the InAs/GaAs system a strategy which allows for the deterministic coupling of a single QD to an S1 PC. This technique is general and can be applied to other PC types [1]. We report high Purcell factors and non-trivial relaxation dynamics for off resonance lines in all fabricated structures.
We will discuss the coupling of an L3 PC with a dilute InAs/GaAs QD system which shows an ultra low threshold stimulated emission. This threshold-less laser is realized even for off -resonance coupling conditions between a few QDs and the L3-PC.
This new body of experimental observations suggests a relaxation of the coupling conditions which is specific to the QDs. We will present evidence that the continuum of states associated with the wetting layer is involved in these relaxed coupling conditions.

[1] A. Badolato et al., *Science* (in press 2005).

Control of Spontaneous Emission by Photonic Crystals

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Control over spontaneous emission of light is essential to quantum optics and to diverse applications such as miniature lasers, LEDs, and single-photon sources for quantum information. Such manipulation not only entails directional spectral changes, but also direction-independent changes of the rate of emission or of the lifetime. The first observation of such emission control with photonic crystals was recently made following the original prediction by Yablonovitch [***Nature*** 430 (2004) 654-657], and it is exhilarating that new realizations arise, also in 2D photonic crystal slabs.

In this presentation, we will discuss various physical aspects of this fundamental subject, illustrated mostly from our work on quantum dots in inverse opals. Examples are the role of an ensemble of light sources, the intricacies of various sources, a comparison between bulk photonic crystals and defect-cavities, and a comparison to theories that typically consider a single two-level atom.

Interaction of Photonic Crystals and Quantum Dots:
Killer Application to Integrated Ultra-Fast
All-Optical Signal Processors

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First demonstration of an ultra-small and ulta-fast symmetric Mach-Zehnder type all-optical switch (PC-SMZ) based on an interaction between nonlinear quantum dots and photonic crystals is reviewed. Technologies essential for achieving such an integrated photonic device are discussed in the field from precise nano-fabrication of GaAs-based two-dimensional photonic crystal slab waveguides to functional waveguide design in light of patterning the SMZ configuration. As a result, transmission spectra in good agreement with calculation and low propagation loss of less than 1 dB/mm are reproducibly exhibited, while directional couplers with arbitrary and wavelength-dependent coupling strengths play important roles of practical beam splitters/couplers. Through the switching operation of the PC-SMZ, possibility of far advancement of the 2DPC-based integrated circuits is concluded.

Tuning holes in two-dimensional Photonic Crystal microcavities: a predictive Fabry-Perot model

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Recently, several works on two-dimensional (2D) Photonic Crystal (PC) microcavities have evidenced the importance of finely tuning the PC geometry at the cavity terminations to achieve high quality factors with wavelength-sized modal volumes. For instance in [1], Q factors of 45,000 have been experimentally achieved through a surprising 10-times Q enhancement induced by a fine shift (60 nm) of the holes surrounding the defect region. We have studied the light confinement in these cavities with a classical Fabry-Perot (FP) model. This approach is original and in comparison with the analysis performed in [1], which is presently being debated [2,3], it leads to a different interpretation of the effects of hole tuning. The existence of an analytical expression for the Q factor highlights new physical effects, namely an improved mode-profile matching at the cavity terminations [4] and a slow wave effect in the cavity.
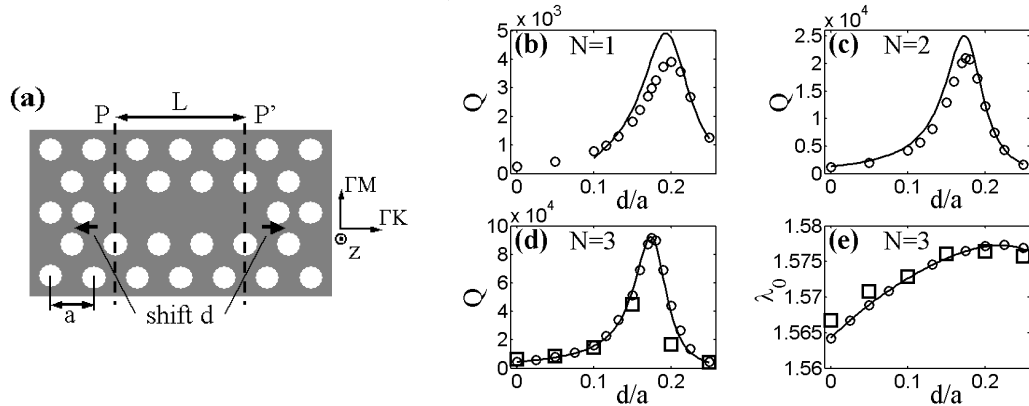
Validation of the FP model. (a) Top view of the investigated cavities formed by filling N holes in a 2D PC. (b), (c) and (d) Q-enhancement for N = 1, 2 and 3, respectively. Comparison between experimental data taken from [1] (squares), rigorous calculation results (circles) and FP predictions (solid curves). (e) Resonance wavelength red-shift for N = 3.

[1]   Y. Akahane, T. Asano, B.S. Song and S. Noda, *Nature* **425**, 944 (2003).
[2]   C. Sauvan, P. Lalanne and J.P. Hugonin, *Nature* **429** (6988), (2004).
[3]   T. Asano and S. Noda, *Nature* **429** (6988), (2004).
[4]   C. Sauvan, G. Lecamp, P. Lalanne and J.P. Hugonin, *Opt. Exp.* **13**, 245 (2005).

Optical Analogue of Electronic Bloch Oscillations

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We report on the observation of Bloch oscillations in light transport through periodic dielectric systems (cover story of Phys. Rev. Lett. **91** [1]). By introducing a linear refractive index gradient along the propagation direction the optical equivalent of a Wannier-Stark ladder was obtained. Bloch oscillations were observed as time-resolved oscillations in transmission, in direct analogy to electronic Bloch oscillations in conducting crystals where the Wannier-Stark ladder is obtained via an external electric field. The observed oscillatory behaviour is in excellent agreement with transfer matrix calculations.

In addition when the linear gradient is strong enough, two minibands can overlap and Zener tunnelling can occur between them, in analogy with the Zener breakdown in semiconductors [2].

[1] R. Sapienza, P. Costantino, D. S. Wiersma, M. Ghulinyan, C. J. Oton, L. Pavesi, Optical Analogue of Electronic Bloch Oscillations, *Phys. Rev. Lett.* **91**, 263902 (2003).

[2] M. Ghulinyan, C. J. Oton, Z. Gaburro, and L. Pavesi, C.Toninelli and D. S. Wiersma, to be published, (2005).